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IMPROVEMENTS RELATING TO SPLICING OF PHOTONIC CRYSTAL FIBRES.

DESCRIPTION

1. BACKGROUND OF THE INVENTION

The present invention relates to a photonic crystal fibre with improved design in order to realize improved splicing properties. These properties concern lower splicing losses and increased mechanical strength. The invention further relates to a splicing between photonic crystal fibres and standard fibres, to methods of making such splices and use of such fibres and/or fibre splicings in various applications.

The Technical Field

In recent years a new class of optical fibres has appeared. The optical guiding mechanism in these fibres is provided by introducing a number of holes or voids in the fibres. These holes typically run parallel with the fibre and extend along the fibre length. The guiding principle can either be based on Total Internal Reflection (TIR) such as in traditional optical fibres, or the Photonic BandGap (PBG) principle. For TIR-based optical fibres the core typically consists of solid glass, which has a larger refractive index than the effective refractive index of the surrounding cladding region, which includes a number of closely spaced holes. For PBG-based optical fibres the refractive index of the core can take any value, since the guiding is given by

the fact that the light cannot propagate through the patterned cladding material. The cladding material would typically consist of carefully placed air holes with a predetermined hole size, distance and pattern.

Both types of optical fibres rely on air holes to give them their optical properties. In general, these types of optical fibres will in the following be called photonic crystal fibres (PCFs). Fibres of this type are also known as microstructured fibres, holey fibres, photonic bandgap fibres, hole-assisted optical fibres, as well as other names may be used.

Many of the PCFs that have recently been developed have characteristics quite dissimilar from conventional, solid glass optical fibres and thus find applications in a range of different fields. To increase the possibilities in which these special fibres can be used in such fields, coupling technologies are very important, both for coupling light between different fibres and for coupling light between PCFs and a variety of optical components.

Transition from small core PCFs to standard fiber is generally difficult. Splice losses are typically high ($\geq$ 0.3 dB - see e.g. Hansen et al., "*Highly Nonlinear Photonic Crystal Fiber with Zero-Dispersion at 1.55 μm*" Optical Fiber Communication Conference 2002 post deadline paper, 2002) and the mechanical strength is poor due to the use of short term heating (sometimes referred to as "cold" splices).

End-sealing of PCFs can provide hermetical sealing of the end and allow increased spot size at the end facet (see e.g. Danish patent application PA 2002 00592). However, the external beam should still be focused to the internal

PCF core area, which for small core fibers can require very small tolerances and result in unstable coupling. Tapering of PCF may be used to provide low loss transition from PCF to standard fibres (see e.g. WO00049435 or EP01199582), but are related with time-consuming and laborious work related to manufacturing of tapered fibre regions. Furthermore, due to significantly reduced fibre diameter (typically a few tens of micrometers), the strength of fibres with tapered regions is lower than for un-tapered fibres.

It is to be understood that the following detailed description is merely exemplary of the invention, and is intended to provide an overview or framework for understanding the nature and character of the invention as it is claimed. The accompanying figures are included to provide further understanding of the invention, and are incorporated in and constitute a part of the invention. The invention is not limited to the described examples. The figures illustrate various features and embodiments of the invention, and together with the description serve to explain the principles and operation of the invention.

2. DISCLOSURE OF THE INVENTION

It is an object of the present invention to provide PCFs that may be spliced with low loss and/or high strength to standard optical fibres. Especially, it is an object to provide small core PCFs that may be spliced with low loss and/or high strength to standard optical fibres.

It is a further object to provide low-loss and/or high strength splices or splicings between PCF and standard optical fibre.

It is a further object to provide methods for making low-loss and/or high strength splice between PCF and standard fibres.

It is a further object of the present invention to provide use of PCFs with improved splice properties and splicings incorporating such PCFs.

Further objects appear from the description elsewhere.

Solution According to the Invention

According to one aspect of the present invention, these objects are fulfilled by providing an optical fibre having an axial direction and a cross section perpendicular to said axial direction, said optical fibre comprising a core region, an inner cladding region and an outer cladding region, wherein said inner cladding region comprises inner cladding features and an inner background material of refractive index n1, and said outer cladding region comprises an outer background material of refractive index n2, and n1 is larger than n2.

In a preferred embodiment, said core region comprises material with a refractive index ncore, and ncore is equal to n1. This provides for example to use similar background material for the inner cladding region and the core region.

In a preferred embodiment, said core region comprises material with a refractive index ncore, and ncore is larger than n1. This allows for example to design an optical fibre with a high nonlinear coefficient, to tailor the dispersion properties of the optical fibre, and/or to tailor the cut-off properties of the optical fibre.

In a preferred embodiment, said core region comprises material with a refractive index ncore, and ncore is smaller than n1. This allows for example to tailor the dispersion properties of the optical fibre, and/or to tailor the cut-off properties of the optical fibre.

In a preferred embodiment, said core region comprises material with a refractive index ncore, and ncore is smaller, equal to, or larger than n2.

In a preferred embodiment, said core region has a diameter smaller than 3.0 μm, for example in a case where the optical fibre is used for generation of nonlinear effects.

In a preferred embodiment, said optical fibre has at least one end being solid, such as a solid end being obtained by collapsing any holes or voids in the end of the fibre. This allows to make a splicing to the solid end of the optical fibre where a high temperature is applied in order to produce a high-strength splicing.

In a preferred embodiment, said optical fibre has at least one end wherein said inner cladding features have been collapsed, such that a guided mode at the fibre end is confined by an index profile determined by the

refractive indices of the solid parts of the core and inner cladding.

In a preferred embodiment, said optical fibre has at least one position along its length where a guided mode at a given wavelength, λ, is confined to the core region by the presence of inner cladding features, such that there is obtained a mode field diameter that is substantially determined by the diameter of the core region, and the optical fibre, furthermore, has at least one end wherein said inner cladding features have been collapsed, such that a guided mode at the wavelength λ at the fibre end is confined by an index profile determined by the refractive indices of the solid parts of the core and inner cladding, such that there is obtained a mode field diameter that is substantially determined by the diameter of the inner cladding region at the fibre end. In this manner there is obtained an expansion of the mode field diameter for a mode guided along the fibre to a mode guided at the fibre end, such that for example a mode matching to a standard optical fibre may be obtained at the fibre end. This provides means for making a low-loss optical splicing with respect to mode matching.

According to a second aspect of the present invention, these objects are fulfilled by providing an optical fibre having an axial direction and a cross section perpendicular to said axial direction, said optical fibre comprising a core region, an inner cladding region and an outer cladding region, said inner cladding region comprises inner cladding features of size, d1, and said outer cladding region comprises outer cladding features of size, d2, and d2 is larger than d1, said optical fibre has at least one end, wherein said inner cladding features are collapsed, and said outer cladding features

are non-collapsed, such that d1 is equal to zero and d2 is larger than zero.

Other objects, features and advantages of the present invention will be more readily apparent from the detailed description of the preferred embodiments set forth below, taken in conjunction with the accompanying drawings.

Definition of terms and expressions

In this application there is made a distinction between the term "refractive index" and the term "effective refractive index". The refractive index is the conventional refractive index of a homogeneous material. For optical fibres of the present invention, the most important optical wavelengths are in the visible to near-infrared regime (wavelengths from approximately 400nm to 2μm). In this wavelength range most relevant materials for fibre production (e.g. silica) may be considered mainly wavelength independent, or at least not strongly wavelength dependent. However, for non-homogeneous materials, such as fibres with voids or air holes, the effective refractive index may be very dependent on the morphology of the material. Furthermore, the effective refractive index of such a fibre may be strongly wavelength dependent. The procedure of determining the effective refractive index at a given wavelength of a given fibre structure having voids or holes is well-known to those skilled in the art (see e.g. Jouannopoulos et al, "Photonic Crystals", Princeton University Press, 1995 or Broeng et al, Optical Fiber Technology, Vol. 5, pp.305-330, 1999).

As appreciated within the field of microstructured fibres, the term "air holes" of the cladding and/or in the core may include holes or voids comprising a vacuum, gas or liquid, said holes or voids being fully or partly filled with a liquid or a gas after production of the microstructured optical fibre.

3. BRIEF DESCRIPTION OF THE DRAWINGS

In the following, by way of examples only, the invention is further disclosed with detailed description of preferred embodiments. Reference is made to the drawings in which

Fig. 1 shows a schematic example of a fibre according to the present invention.

Fig. 2a and Fig. 2b shows schematic examples of other fibres according to the present invention.

Fig. 3 shows a schematic example of yet another fibre according to the present invention.

Fig. 4 shows a schematic example of a fibre profile for a fibre according to the present invention.

Fig. 5 shows a schematic example of an end of a fibre according to the present invention.

Fig. 6 shows a schematic example of a fibre profile for an end of a fibre according to the present invention.

Fig. 7 shows a schematic example of a fibre according to the present invention. The figure illustrates the

collapse of inner and outer cladding features in an end of the fibre, and that these features are open in a cross-section along the longitudinal direction of the fibre.

Fig. 8 shows a schematic example of another fibre according to the present invention.

Fig. 9 shows a schematic example of an end of another fibre according to the present invention.

Fig. 10 shows a schematic example of an optical fibre splicing according to a preferred embodiment of the present invention.

Fig. 11 shows a schematic example of an optical fibre according to a preferred embodiment of the present invention. The optical fibre is a photonic bandgap fibre.

Fig. 12 shows a schematic example of an optical fibre preform according to a preferred embodiment of the present invention.

4. DETAILED DESCRIPTION

In order to present the invention, the proceeding description shall be based on examples. The examples act to illustrate the concepts and design ideas that underlie the invention. It is to be understood that the examples are merely illustrative of the many possible specific embodiments which can be devised from the present invention as well as there exists many possible applications that may be devised from the principles of the invention. The presented examples are not intended to limit the scope of the invention.

The present invention disloses in a preferred embodiment an optical fibre as shown schematically in Fig. 1. The fibre comprises a core region 10 and a cladding region comprising an inner cladding region 11 and an outer cladding region 12. The inner cladding region comprises low-index inner cladding features 13 and a background material of refractive index n1. The outer cladding region comprises a background material of refractive index n2. The optical fibre is characterized in that n1 is larger than n2. Optionally, the outer cladding may comprise outer cladding features 21 – as shown schematically in Fig. 2a and Fig. 2b for other preferred embodiments. The core region 10, 20, 25 may comprise a refractive index profile, such that the core region comprises material with a refractive index, ncore, being different from the refractive index, n1, of a material in the inner cladding region – as shown schematically in Fig. 1 and Fig. 2b. Hence, ncore may be higher or lower than n1. In order to tune various properties of the optical fibre, it may be preferred to have a special refractive index profile of the core region – for example for tuning dispersion properties and nonlinear coefficient of the optical fibre. To provide largest degree of flexibility the present invention includes both preferred embodiments with ncore higher and lower value than n1. For nonlinear applications for example, it may be preferred to have ncore larger than n1 to increase the nonlinear coefficient of the optical fibre. Alternatively, the fibre core 20, 30 may comprise a material of similar refractive index as the inner cladding region – shown schematically in Fig. 2a and Fig. 3 for yet other preferred embodiments of the present invention. Naturally, any combination that may be obtain from the above-described embodiments are also covered by

the present invention, such as for example a fibre as shown in Fig. 3 that further comprises outer cladding features.

The fibre in Fig. 2a comprises a core region 20 with a material of refractive index ncore, and an inner cladding region with an inner background material of refractive index n1 and inner cladding features with a diameter d1. The fibre further comprises an outer cladding region with an outer background material of refractive index n2 and outer cladding features with a diameter d2. The fibre is characterized in that n1 is larger than n2. Preferably, the innercladding region comprises a single or two rings of holes or voids around the core region. The fibre in Fig. 2b resembles the fibre in Fig. 2a, but has ncore different than n1, such as larger or smaller than n1.

Fig. 4 shows schematically an effective index profile of a fibre according to a preferred embodiment. The radial distance labeled r_{PCF} is equal to the radius of the core region, as defined by the half-distance between two opposite innermost inner cladding features. The radial distance labeled r_{solid} is equal to the radius or largest dimension of the inner cladding background material. The distance $2r_{PCF}$ and $2r_{solid}$ are shown in Fig. 3 for illustrative purposes.

Other effective index profiles are also relevant, such as for example a profile that may have a higher effective refractive index of the outer cladding compared to the inner cladding.

The present inventors have realized that the here-disclosed PCFs having a higher background refractive index in an inner cladding compared to an outer cladding,

are especially advantageous for the realization of low or reduced splicing losses. This may be understood from the following description.

In addition to the effective index-guiding properties provided by microstructured inner cladding for the fibres in Fig. 1 to 3, (obtained using holes or voids), an additional (weaker) index guiding region is provided by the index difference between the inner and outer cladding background material. This weaker guidance is substantially suppressed by the presence of holes or voids in the inner cladding. However, at a fibre end or at a fibre splice, where the holes or voids in the inner cladding region may be collapse, the weaker guidance may become dominant. In the case of collapsed holes or voids in the inner cladding region, the fibre will be characterized by an enlarged core region - defined by the index profile in the absence of holes (or collapsed holes). Hence, it becomes possible to expand the core region in a well-defined manner by design of the inner cladding features, the index difference between the inner and outer background cladding material and the dimensions of the various features of the fibre (including size and separation of inner cladding features and size of inner cladding cladding region).

Fig. 5 shows schematically a fibre according to a preferred embodiment of the present invention at a collapsed end. This collapsed end may be at a spliced end, a connectorized end or a "loose" end. The inner and any optional outer cladding voids or holes have been collapsed and the waveguiding is provided by the refractive index difference between the regions 50 (core) and 51 (cladding). Since the refractive index profile of the fibre at the collapsed end may be dimensioned

accurately be choice of the material and dimensions, a given mode field diameter (MFD) at the collapsed end may be obtained. Preferably, the collapsed end provides a MFD that matches a standard (solid) optical fibre. Fig. 6 shows schematically the refractive index profile at the collapsed end. In preferred embodiment, the radius of the core at the collapsed, r'_{solid} end is in the range from 2 µm to 12 µm.

In a preferred embodiment, the core diameter and the refractive index profile of the fibre at the collapsed end is chosen such that the fibre at the collapsed end has a V-parameter below 2.4 at a given wavelength, in order for the fibre at the collapsed end to be single mode. As an example, the core diameter at the collapsed end 50 may have a largest dimension of around 4.7 um (r'_{solid} = 2.35 µm), an index difference between the region 50 and 51 of around 3*10-2 (n1-n2 = 3*10-2), such that the fibre at the collapsed end is single mode at a wavelength of 1.55 µm. In further preferred embodiments, the fibre has an outer diameter of around 125 µm.

It is valuable to consider a fibre according to one of the various preferred embodiments in its longitudinal direction - as shown schematically in Fig. 7, the fibre comprises a first end 70, referred to as a collapsed end, where the fibre has been treated such that the inner cladding features have been collapsed. Typically, this collapse is performed using heat-treatment as shall be discussed in further detail later. Preferably (but not required) the optional outer cladding features have also been collapsed. Thereby, there can be obtained an adiabatic transition from a (small) mode confined substantially by the inner cladding features at a given position 71 away from the collapsed end 70 to a (larger)

mode confined by the refractive index difference at the collapsed end 70. Hence, the present invention provides microstructured optical fibres that at a fibre end may act as a standard (solid) index-guiding fiber. Therefore, the ability to treat the collapsed end of the PCF as an end of a standard optical fibre enables splicing at standard conditions yielding low splicing losses and high strength. In particular, this enables splicing at conditions using heat treatment parameters such as heat exposure time and temperature that are known from splicing technology of standard optical fibres. Naturally, PCFs according to the present invention may be spliced to both standard optical fibre, as well as to other PCFs according to the present invention with low losses and/or high strength.

In the majority of the fibre length (exemplified by the position 71, where the PCF has a cross-section with non-collapsed inner cladding features), the incurred index-step for the microstructured cladding (the index difference between n1 and n2) is significantly smaller than the effective index difference between the core region and the inner cladding region. Hence, the index difference between n1 and n2 will only slightly - and preferably negligibly - change the optical properties of the PCF, as compared to a PCF with uniform cladding background refractive index. Intuitively, the fibre may be seen to have incorporated two waveguiding profiles; a strong profile in the case of non-collapsed holes (position 71) that confines light tightly in a small core, and a weaker profile in the case of the collapsed holes (position 70) that confines light in a larger core. Alternatively worded, the PCF may be seen to have "embossed" the refractive index profile of a standard fibre into the solid parts of the PCF. In the case where

the holes or voids are collapsed, the "embossed" index profile stands out and the PCF is thereby brought to become similar and compatible with standard fibres. Since the "embossed" profile (responsible for the waveguiding at position 70) is weaker than the microstructured profile (responsible for the waveguiding at position 71), the fibre may be kept single mode at position 70 even though the core size here is increased as compared to position 71. In fact, a PCF may be made that is in theory multi-mode at position 71, but single mode at position 70. This is possible due to a strong decrease of the effective refractive index by air holes or voids in the inner cladding, as compared to index changes that may be obtained using traditional silica-doping techniques.

As "embossed" profile, the present invention covers all known refractive index profiles from standard optical fibre technology. Hence, any such refractive index profiles in combination with any known hole or void structure or design of PCFs are covered by the present invention for as long as the inner cladding features have been collapsed at at least one fibre end. This provides compatibility in terms of low losses and/or high mechanical strength of splicings between PCFs and various types of standard optical fibres or other PCFs.

The ideas and methods disclosed in the present invention are especially useful for small core fibers with small mode field areas. The collapsed index-guiding fiber end 70 is preferably single mode. Examples of small core PCFs are highly nonlinear fibers and dispersion compensating fibers. Hence, the present invention provides technical advantages in terms of reduced splice loss and/or improved splice strength for such fibres and applications using such fibres. Hence, the present invention also

covers use of the here-disclosed fibres for various applications, including nonlinear fibres and dispersion compensating fibres.

Preferred embodiments of the present invention covers PCFs realized in silica technology with air holes or voids. In preferred embodiments, the core and inner cladding background material comprises Ge-doped silica (optionally various other dopants, such as Al, La, and/or various rare earths could be included), and the outer cladding background material comprises pure silica. In another preferred embodiment, the core and the inner cladding background material comprises pure silica and the outer cladding background material comprises silica doped with index decreasing material, such a Fluorine and/or Boron. In preferred embodiments, the core has a relatively small size, such as a core diameter ($2r_{PCF}$) of less than 3.0 µm, such as less than 2.0 µm. In order to reduce leakage losses of PCFs, it is often preferred that more than 5, such as more than 7 rings or layers or periods of holes or voids surround the core (this number being taken as the total number of rings in the inner and outer cladding region).

For a fibre according to the present invention, it should be clear that the parameter r'_{solid} will be smaller than r_{solid} (due to the collapse of the inner holes or voids). Hence, in order to obtain a desired core size at the collapsed end (a given r'_{solid}), r_{solid} should be designed larger than the desired core size. The exact dimensioning of r_{solid}, depends on the various features of the PCF, most importantly the filling fraction of the inner cladding region (this filling fraction being determined by the size and arrangement of the inner cladding features).

The ideas of the present inventors may also be utilized in single material PCFs. An example is shown in Fig. 8 where the PCF comprises features of at least two different sizes. Surrounding the core 80, there is placed in radial direction; inner cladding features 81 of size d1, and further away from the core there is placed a number of outer cladding features 82 of size d2. In a first cross-section at a first longitudinal position of at least 1 μm away from the end facet or spliced end, the fibre is characterized by d1, d2 > 0 and d2 > d1. At at least one of end of the fibre, the fibre is further characterized by the inner cladding features being collapsed and the outer cladding features being non-collapsed, such that d1=0 and d2>d1. Fig. 9 shows schematically the fibre at the end or the spliced end. The collapse of the inner cladding features causes the outer cladding features 90 to provide the confinement of light to the (enlarged) core region 91. In this manner, it is obtained that the optical fibre has a small MFD over the majority of its length, and at an end or a spliced end that the MFD is expanded. By dimensioning of the inner and the outer cladding features, the MFD both in the fibre length and at the end or the spliced end may be accurately controlled. Hence, also by this alternative embodiment of the present invention, it becomes possible to provide a PCF with a small MFD (for example MFD of less than 3.0 um) that is spliced with low loss to a standard fibre (for example with a MFD of more than 4.0 um). The low loss is obtained by matching the MFD of the PCF at its end or spliced end by collapsing inner cladding features. It should be clear that the same technical advantages in terms of mode matching at the fibre splicing as discussed for the fibres in Fig. 1 to 7 are obtained for the fibre in Fig. 8 and 9. However, the technical advantages in the case of Fig. 8 and 9 are

obtained without the use of index difference between the inner and outer cladding background material, but with the use of different-sized inner and outer cladding features and non-collapsed outer cladding features at the fibre end or spliced end.

The collapse of the inner cladding features (typically holes or voids) for all embodiments of the present invention may be obtained by applying a heat treatment to the fibre end. In the case of larger outer cladding features, the smaller size of the inner cladding holes or voids compared to the outer cladding holes or voids results in a larger surface tension for the innermost holes or voids. This larger surface tension will cause the innermost holes or voids to collapse at a lower temperature and/or shorter time of heat treatment. The outer cladding feature may also partly collapse - as indicated in Fig. 9, where the outer cladding features 90 are reduced in size as compared to in Fig. 8.

Commercially available splicing equipment, such as for example Vytran FS2000, allows control of parameters such as heating time and amount of heat to allow fabrication of the fibres end facet or spliced ends according to the various preferred embodiments of the present invention. For the embodiments where all holes or voids are collapsed at the fibre end, it should be clear that the procedure for collapsing holes or voids is even more simple than in the case described above with collapsed inner cladding features and non-collapsed outer cladding features. To a person skilled in the art of operating splicing equipment, it is possible provide sufficiently long heat treatment for all holes or voids to collapse at the fibre end or during fibre splicing. Optionally, a less-than-atmospheric pressure may be applied to the

holes or voids of the fibre to facilitate their collapse. Especially, in the case of a fibre end with all holes or voids being collapsed, such as the embodiments comprises an index difference between the inner and outer cladding background material, splicing of the microstructured fibre to other fibres, typically standard (solid) fibre may be performed using standard splicing techniques that provides high strength. The collapse and splicing to standard fibre may either be performed in a single step or in two or more steps using the Vytran FS2000 equipment.

Fig. 10 shows an example of use of a microstructured optical fibre according to a preferred embodiment of the present invention. The microstructured optical fibre 101 is spliced to a standard (solid) optical fibre 102. The microstructured optical fibre is characterized by a core doping profile 104 and a doped profile in an inner cladding 105. The microstructured optical fibre further comprises a number of holes or void over a given length - exemplified at the position 103. The standard optical fibre comprises a doped profile 106 to provide given optical properties of the fibre - for example single mode operation at a given wavelength. The profile 105 may be adapted to the profile 106 such that there is a high overlap between a mode guided by the profile 105 and the profile 106 - such as a mode overlap of more than 80%. The profiles 104 and 105 in combination may also be adapted or designed such that there is a mode overlap of more than 80% to a mode guided by the profile 106. The two fibres may be spliced together by applying a heat-treatment to both fibre ends such that the holes or voids of the microstructured optical fibre collapse and the glass in both fibres becomes soft. By pushing the two fibres together they may be fused together. The heat

treatment and the fusing may be performed using the afore-mentioned Vytran splicing equipment. This equipment also allows to push the two fibre against eachother I na controlled manner. This may for example be utilized to provide a substantially uniform outer diameter of the microstructured optical fibre along its length (including at the spliced end where the holes have been collapsed). Hence, an optical fibre splicing or splice may be obtained between a microstructured optical fibre and a standard optical fibre, where tapering is avoided. Since tapering provides increased risk of mechanical breakage due to smaller outer fibre diameter, it is an advantage of the here disclosed method and use of microstructured optical fibres, that substantially uniform outer fibre diameter may be obtained across a splicing.

Fig. 11 shows a schematic example of the cross-section of yet another fibre according to the present invention. The optical fibre may guide light by photonic bandgap effects and is characterized by a low-index core region and a periodic cladding region obtained by the use of periodically placed voids or holes in the inner and outer cladding region. The fibre is characterized by a hollow core region 110, and an inner cladding region comprising an inner background material 111 with refractive index n1 and inner cladding features 112 with diameter d1, and an outer cladding region comprising an outer background material 114 with refractive index n2 and outer cladding features 113 with diameter d2, and n1 is larger than n2.

Fig. 12 shows a schematic example of a cross section of a preform for fabricating an optical fibre according to various preferred embodiments of the present invention. The preform comprises a core element 120 with a refractive index ncore, a number of inner cladding

elements 121 comprising material with refractive index n1, and a number of outer cladding elements 122 comprising material with refractive index n2, and n1 is larger than n2. In order to tune various properties of the final fibre, it is preferred that the is a flexibility in tuning ncore. Since, ncore is chosen separately from n1 by the individual element 120, ncore may be chosen to be similar, smaller than or larger than n1.

In preferred embodiments, the optical is made using silica based glasses, such that certain parts of the preform elements are realized using pure silica and other parts are realized using doped silica. Various dopants may be used to provide a given refractive index level or profile as well as active dopants may be used to provide fibre for e.g. amplifiying or lasing applications.

In order to stabilize the drawoing of the preform, it is often preferred to use an overcladding tube 123 and optionally various stuffing or buddering elements to further fill the overcladding tube.

Preferably, the number of inner cladding elements is in the range of 6 to 18 in order to obtain one or two rings of inner cladding features around the core region in the final fibre.

The preform may be drawn into optical fibre using one or more steps - as would be known to a person skilled in the art of producing PCFs.

While the invention has been particularly shown and described with reference to particular embodiments, it will be understood by those skilled in the art that

various changes in form and details may be made therein without departing from the spirit and scope of the invention, and it is intended that such changes come within the scope of the following claims.

Modtaget PVS

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IMPROVEMENTS RELATING TO SPLICING OF PHOTONIC CRYSTAL FIBRES.

CLAIMS

1. An optical fibre having an axial direction and a cross section (71) perpendicular to said axial direction, said optical fibre comprising

(a) a core region (10, 20, 25, 30, 110) for propagating the light to be transmitted in the longitudinal direction of the optical fibre; and

(b) a microstructured cladding region, said cladding region surrounding said core region and comprising an inner cladding region with inner cladding features (13, 22, 112) of size d1 being arranged in an inner cladding background material (11, 21, 111) with refractive index n1, and an outer cladding region with an outer cladding background material (12, 24, 114) with refractive index n2; and

(c) n1 being larger than n2.

2. The optical fibre according to claim 1, wherein said fibre comprises at least one fibre end (70) having collapsed inner cladding features.

3. The optical fibre according to claim 1 or 2, wherein said outer cladding region comprises outer cladding features (23) of size d2.

4. The optical fibre according to any of the claims 1 to 3, wherein said fibre comprises a fibre end (71) having collapsed inner cladding features and collapsed outer cladding features.

5. An optical fibre having an axial direction and a cross section perpendicular to said axial direction, said optical fibre comprising

(a) a core region (80) for propagating the light to be transmitted in the longitudinal direction of the optical fibre; and

(b) a microstructured cladding region, said cladding region surrounding said core region and comprising an inner cladding region with inner cladding features (81) of size d1 being arranged in an inner cladding background material with refractive index n1, and an outer cladding region with outer cladding features (82) of size d2 being arranged in an outer cladding background material with refractive index n2, and

(c) d2 being larger than d1; and

(d) said optical fibre comprises at least one fibre end (70) having collapsed inner cladding features.

6. The optical fibre according to any of the claims 1 to 5, wherein n1 and n2 are different by less than 2%, such as less than 1%, such as less than 0.5%.

7. The optical fibre according to any of the claims 1-6, wherein the optical fibre comprises silica-based

materials and the inner cladding features and any optional outer cladding features are holes or voids.

8. The optical fibre according to any of the claims 1-7, wherein said core region comprises material with a refractive index ncore, and ncore is equal to n1.

9. The optical fibre according to any of the claims 1-7, wherein said core region comprises material with a refractive index ncore, and ncore is larger than n1.

10. The optical fibre according to any of the claims 1-7, wherein said core region comprises material with a refractive index ncore, and ncore is smaller than n1.

11. The optical fibre according to any of the claims 1-10, wherein said core region comprises material with a refractive index ncore, and ncore is smaller, equal to, or larger than n2.

12. The optical fibre according to any of the claims 1-11, wherein said core region has a diameter smaller than 3.0 μm.

13. The optical fibre according to any of the claims 1-12, wherein said optical fibre has at least one fibre end (70) wherein said inner cladding features have been collapsed, such that a guided mode at the at least one fibre end is substantially confined by the index difference between n1 and n2.

14. The optical fibre according to any of the claims 1-12, wherein said optical fibre has at least one position, position 1 (71), along its length where a guided mode at a given wavelength, λ, is confined to the core region by

the presence of inner cladding features, such that there is obtained a mode field diameter that is substantially determined by a diameter of the core region, and the optical fibre, furthermore, has at least one fibre end (70) wherein said inner cladding features have been collapsed, such that a guided mode at λ at the at least one fibre end (70) is confined by an index profile determined by solid material parts of the core region and the inner cladding region, such that there is obtained a mode field diameter that is substantially determined by the diameter of the core region at position 1 (71) and a mode field diameter that is substantially determined by the diameter of the inner cladding region at the at least one fibre end (70).

15. The optical fibre according to claim 14, wherein λ is in the range from 0.4 μm to 2.0 μm.

16. The optical fibre according to any of the claims 1-15, wherein the core region has a largest dimension, r_{PCr}, being in the range of 0.8 μm to 3.0 μm.

17. The optical fibre according to any of the claims 1-16 wherein the inner cladding region has a largest dimension, r_{solid}, being in the range of 3.0 μm to 15.0 μm.

18. The optical fibre according to any of the claims 2-17, wherein a core region (50) at the fibre end (70) has a largest dimension, r'_{solid}, being in the range of 2.0 μm to 12.0 μm.

19. A method for making an optical fibre according any of the claims 2 to 4 or 6 to 18, wherein said method comprises heat-treatment of at least one end of an

optical fibre according to claim 1 such that inner cladding features collapse.

20. A method for making an optical fibre according any of the claims 5 to 18, wherein said at least one end is heat-treated such that inner cladding features collapse.

21. An optical fibre splicing comprising the optical fibre according to any of the claims 1-18 and a standard optical fibre.

22. An optical fibre splicing comprising the optical fibre according to any of the claims 1-18 and a microstructured optical fibre.

23. An optical fibre splicing comprising the optical fibre according to any of the claims 1-18 and another optical fiber according to any of the claims 1 to 18.

24. A method for making an optical fibre splicing according to any of the claims 21 to 23, wherein said method comprises heat-treatment of an end of an optical fibre according to any of the claims 1 to 18 and fusing a standard optical fibre or a microstructured optical fibre or another optical according to any of the claims 1 to 10 onto said end.

25. An article comprising an optical fibre according to any of the claims 1 to 18, or an optical fibre splicing according to any of the claims 21 to 23, wherein said article is a non-linear fibre component.

26. An article comprising an optical fibre according to any of the claims 1 to 18, or an optical fibre splicing

according to any of the claims 21 to 23, wherein said article is a dispersion compensating fibre component.

27. An article comprising an optical fibre according to any of the claims 1 to 18, or an optical fibre splicing according to any of the claims 21 to 23, wherein an outer diameter of the optical fibre is substantially uniform along the axial direction.

28. A method according to claim 24, wherein ends of two optical fibres are pushed towards each other during fusing to obtain a substantially uniform outer fibre diameter across said optical fibre splicing.

29. A preform for making an optical fibre, wherein said preform comprises

(a) at least one core element (120) comprising material with refractive index ncore,

(b) inner cladding elements (121) comprising material with refractive index n1,

(c) outer cladding elements (122) comprising material with refractive index n2;

characterized in that n1 is larger than n2.

30. A preform according to claim 29, wherein ncore is higher than n1.

31. A preform according to claim 29, wherein ncore is equal to n1.

32. A preform according to claim 29, wherein ncore is lower than n1.

33. A preform according to any of the claims 29 to 32, wherein said core element is a pure silica rod.

34. A preform according to any of the claims 29 to 32, wherein said core element is a rod comprising doped silica, such as Ge, Al, F, B, Er, or Yb doped silica, or combinations of these.

35. A preform according to any of the claims 29 to 34, wherein said inner cladding elements are pure silica tubes.

36. A preform according to any of the claims 29 to 34, wherein said inner cladding elements are tubes comprising doped silica, such as Ge, Al, F, B, Er, or Yb doped silica, or combinations of these.

37. A preform according to any of the claims 29 to 36, wherein said outer cladding elements are pure silica tubes.

38. A preform according to any of the claims 29 to 36, wherein said inner cladding elements are tubes comprising down-doped silica, such as F doped silica.

39. A preform according to any of the claims 29 to 38, wherein said preform comprises an overcladding tube (123).

39. A preform according to any of the claims 29 to 38, wherein said preform comprises an overcladding tube (123).

40. A preform according to any of the claims 29 to 39, wherein said preform comprises buffer elements, such as rods and/or tubes with a smaller cross-sectional size than the outer cladding elements.

41. A preform according to any of the claims 29 to 40, wherein said preform comprises a given number of inner cladding elements, and said number is in the range from 6 to 18, such as equal to 6.

42. An optical fibre drawn from a preform according to any of the claims 29 to 41.

43. An optical fibre according to any of the claims 1 to 18, wherein said optical fibre has been drawn from a preform according to any of the claims 29 to 41.

44. An optical fibre according to any of the claims 1 to 18, wherein said optical fibre is an index-guiding photonic crystal fibre.

45. An optical fibre according to any of the claims 1 to 18, wherein said optical fibre is a photonic bandgap fibre.

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IMPROVEMENTS RELATING TO SPLICING OF PHOTONIC CRYSTAL FIBRES.

ABSTRACT

An optical fibre having an axial direction and a cross section (71) perpendicular to said axial direction, said optical fibre comprising: a core region (10, 20, 25, 30, 110) for propagating the light to be transmitted in the longitudinal direction of the optical fibre; and a microstructured cladding region, said cladding region surrounding said core region and comprising an inner cladding region with inner cladding features (13, 22, 112) of size d1 being arranged in an inner cladding background material (11, 21) with refractive index n1, and an outer cladding region with an outer cladding background material (12, 24) with refractive index n2, said n1 being larger than n2; an optical fibre with an end (70) having collapsed inner cladding features, a method of making such an end, a fibre splicing comprising such an optical fibre and a standard optical fibre, a method of making such a fibre splicing, and use of such fibres and fibre splicings, and a preform for making such an optical fibre.

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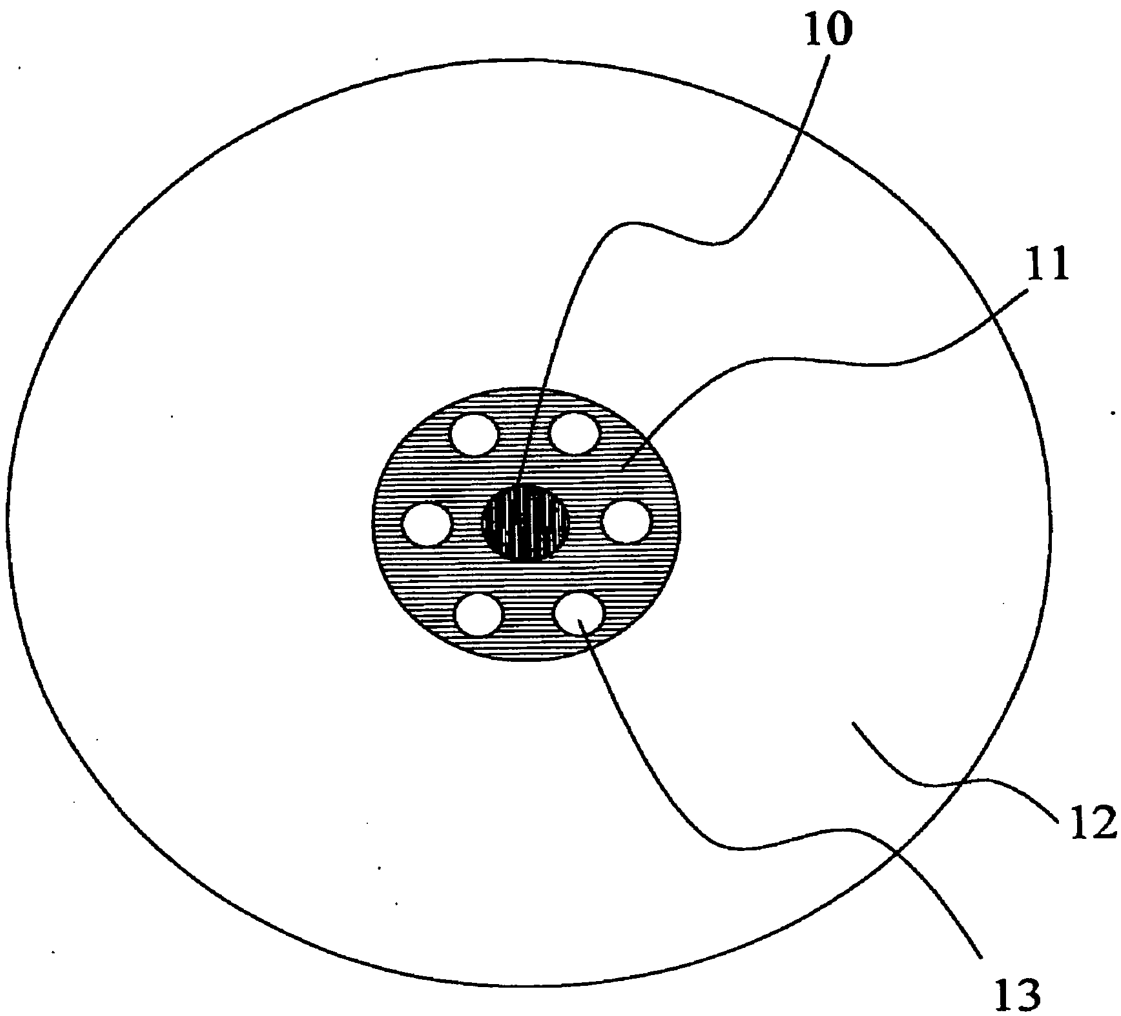

Fig.1

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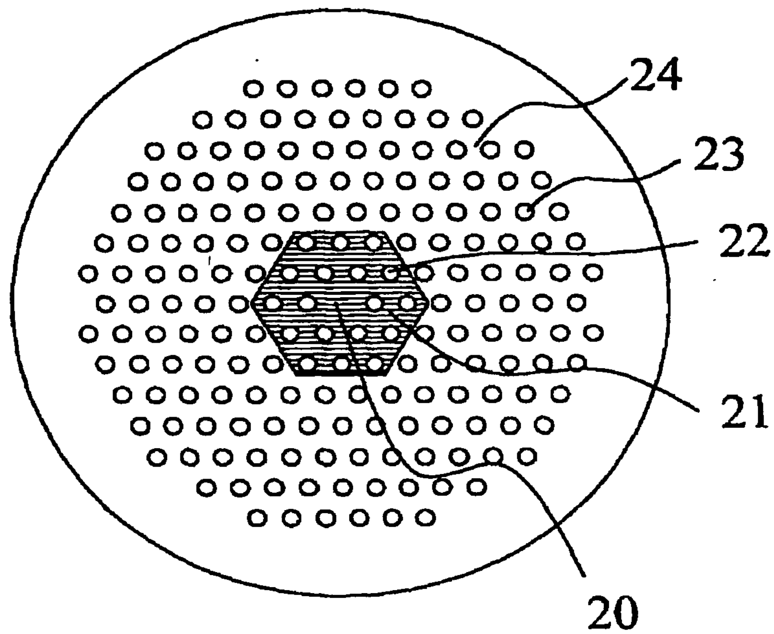

Fig. 2a

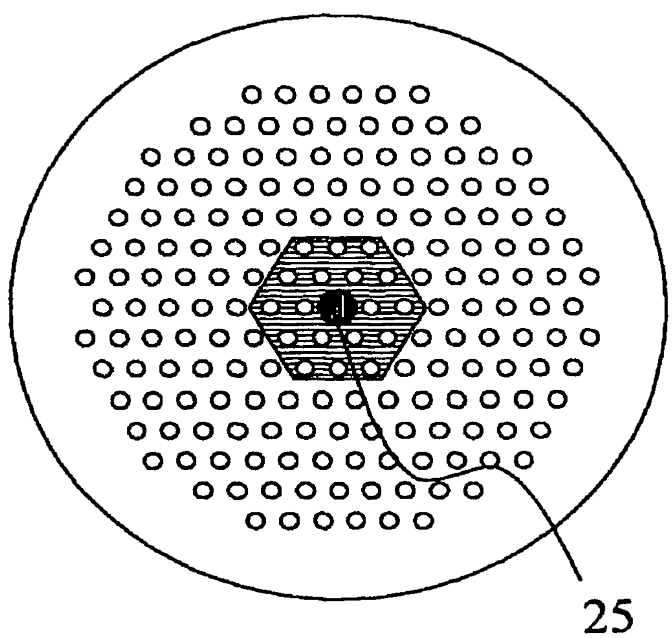

Fig. 2b

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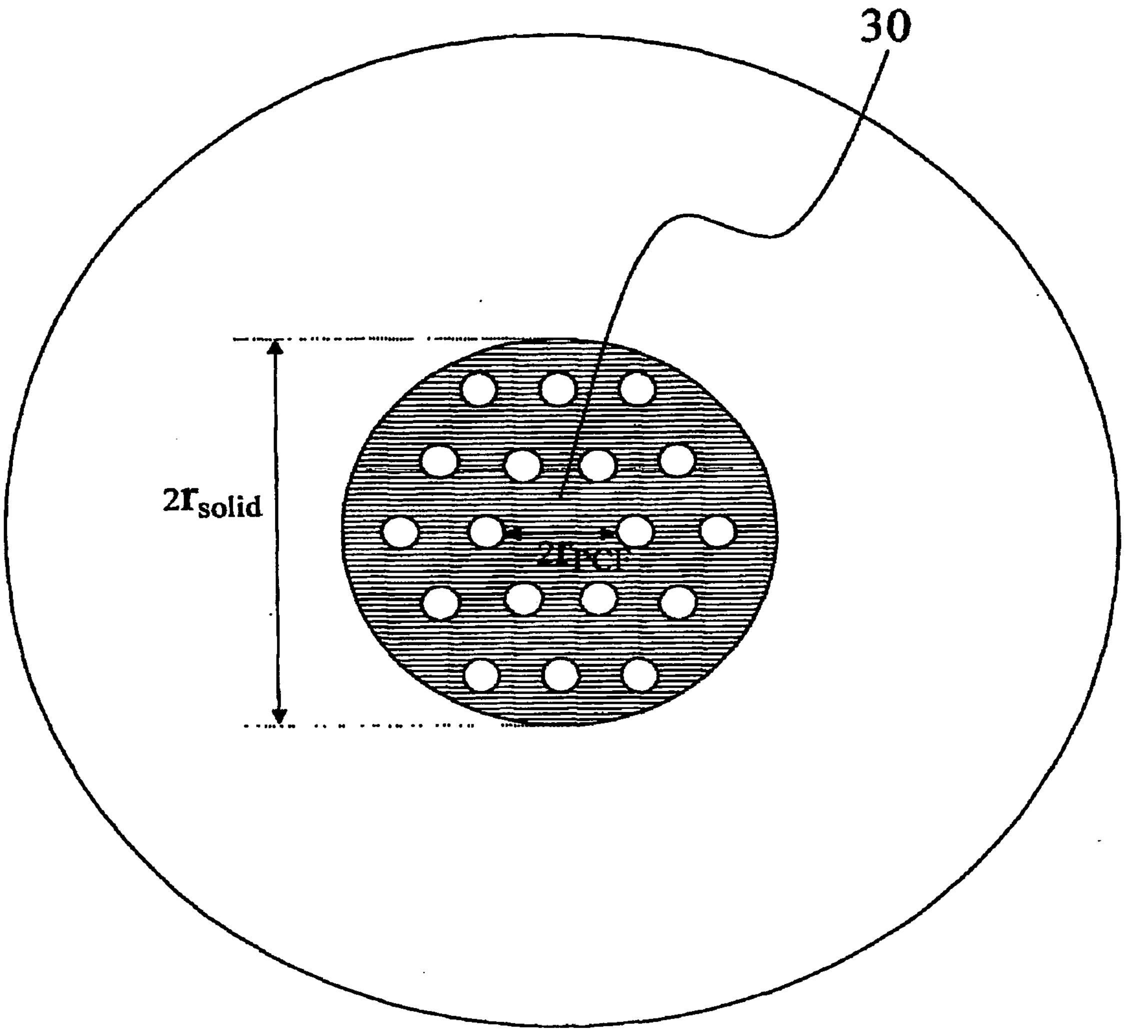

Fig. 3

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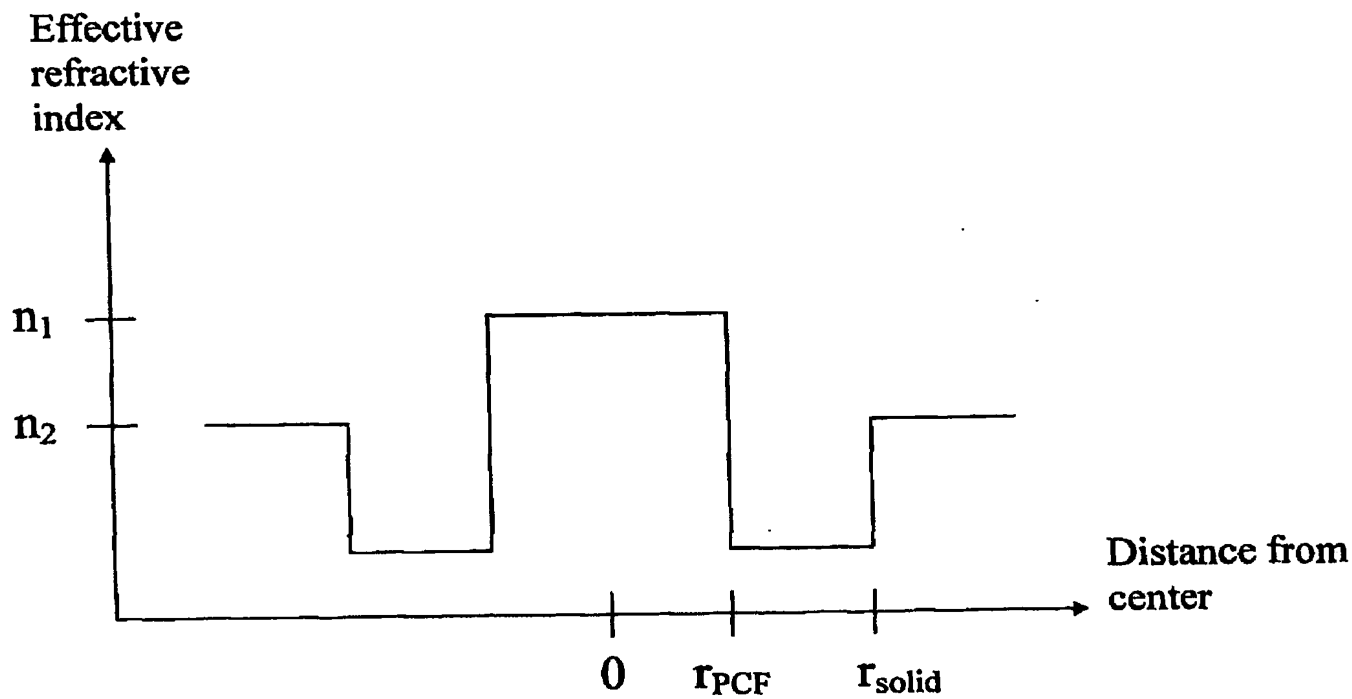

Fig.4

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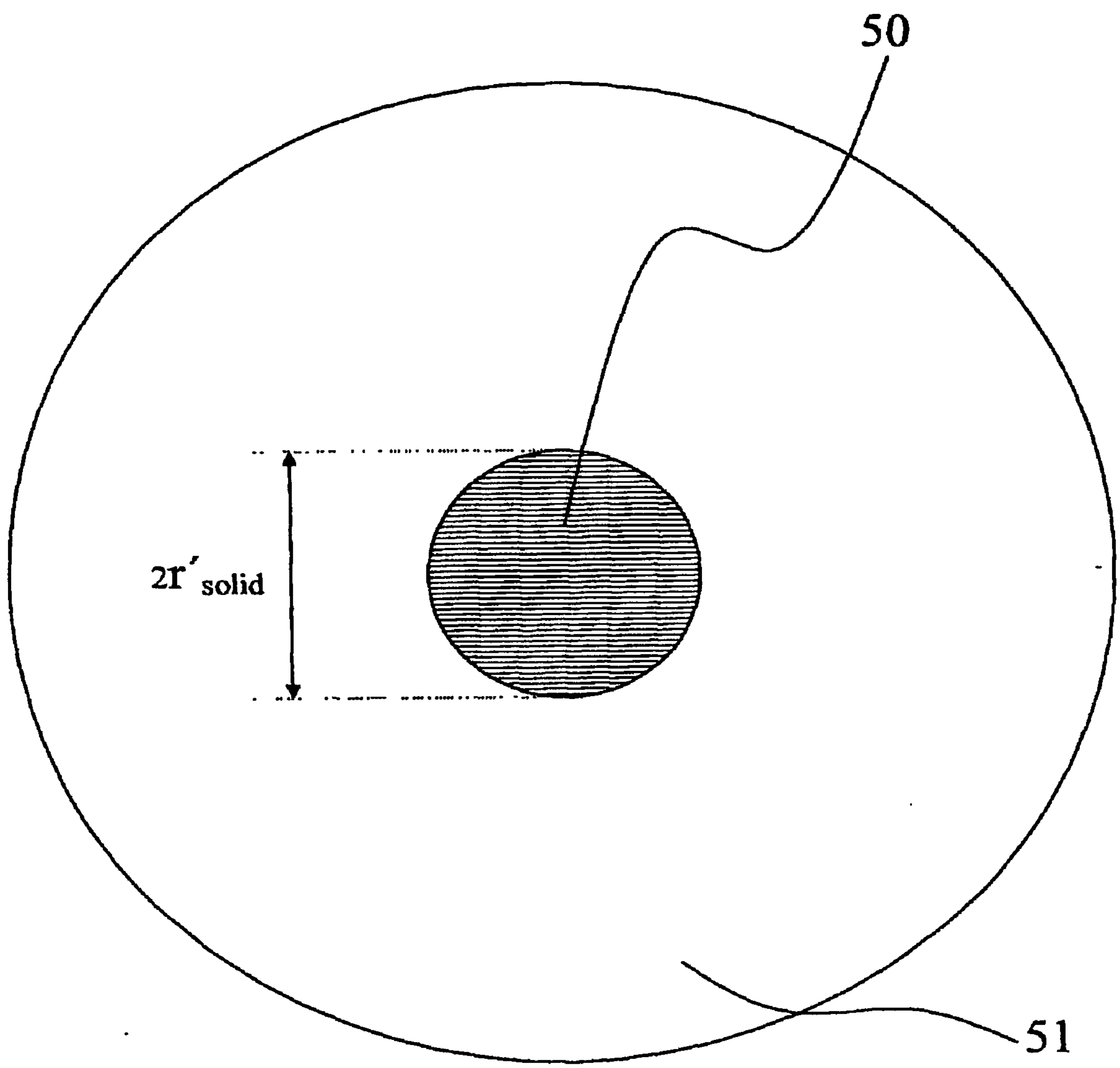

Fig.5

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Fig.6

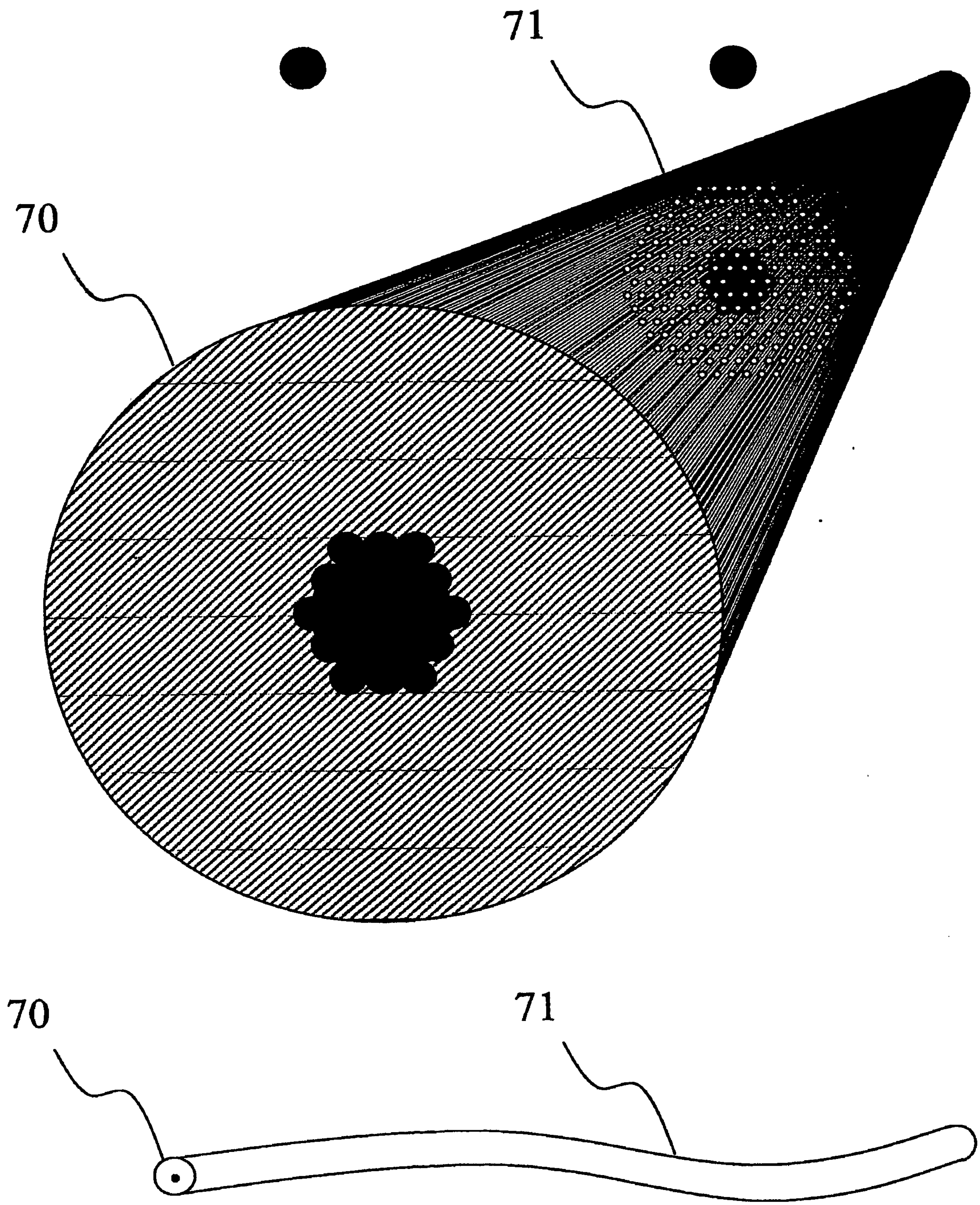

Fig.7

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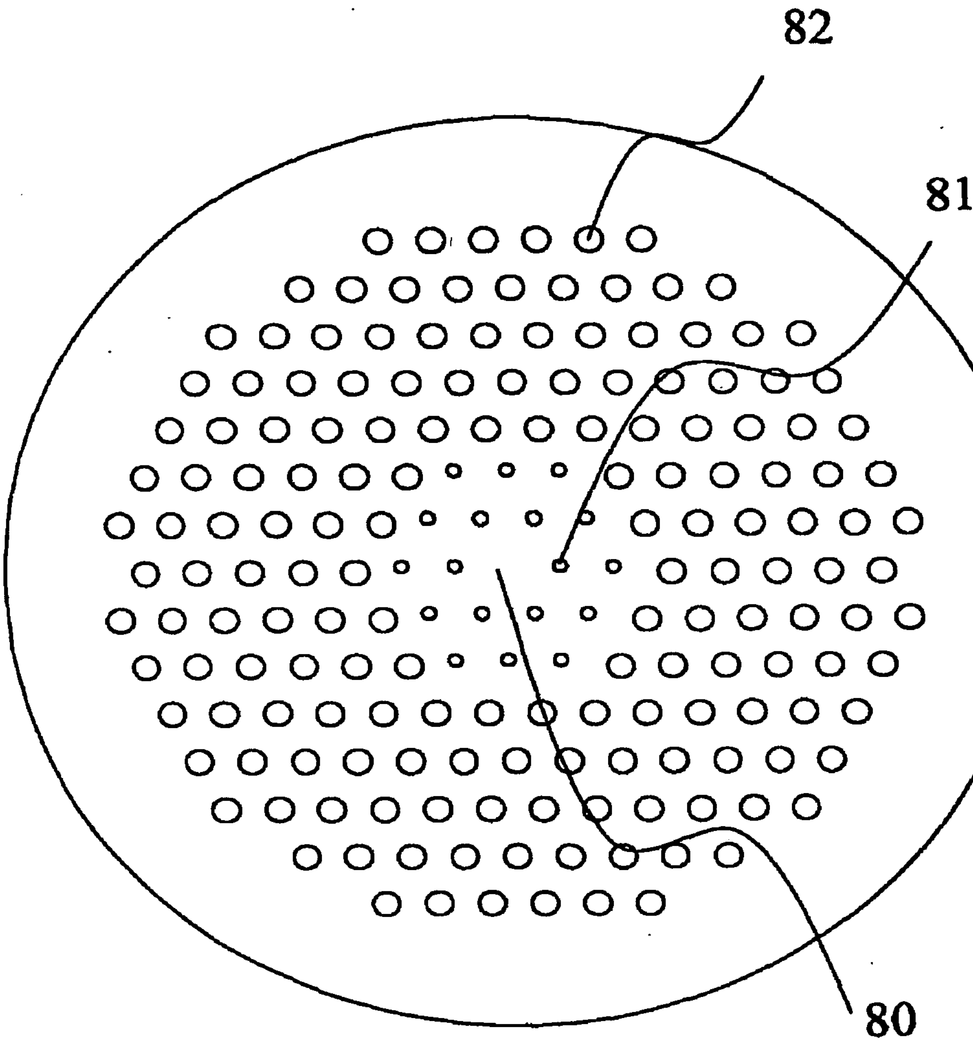

Fig.8

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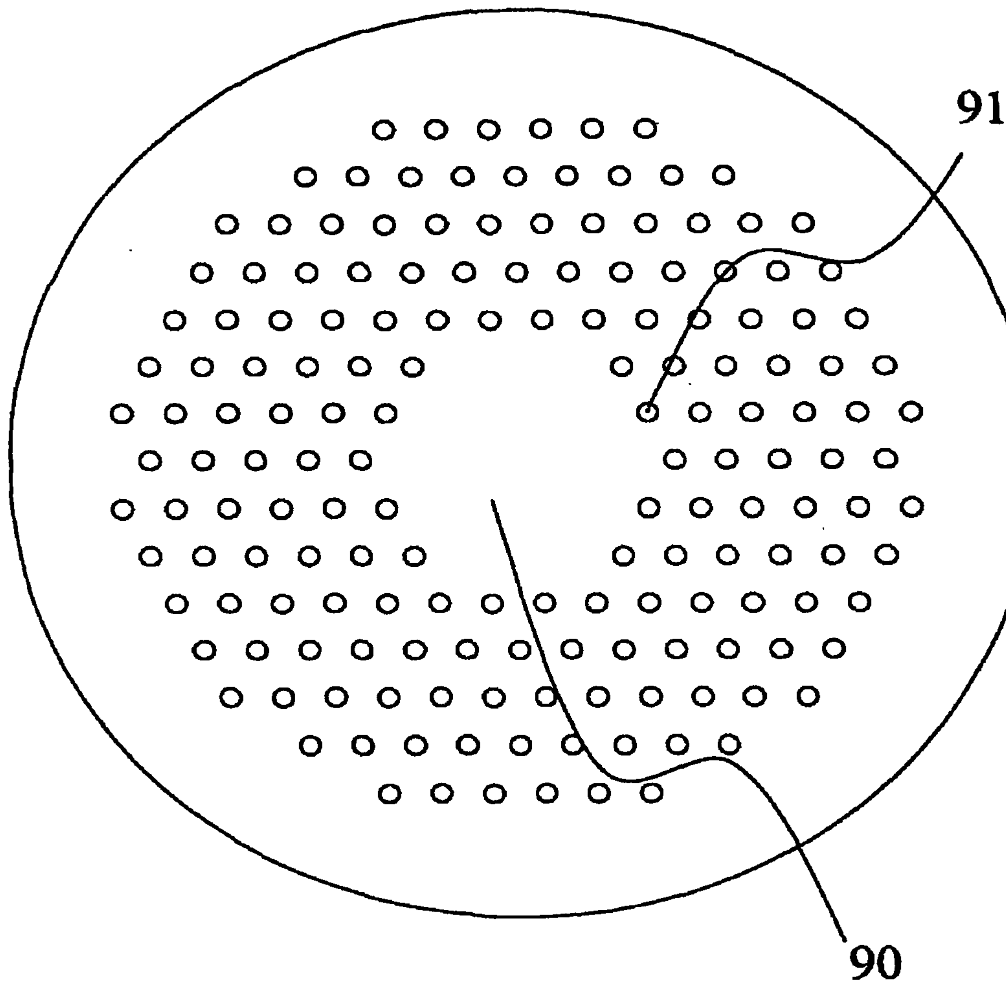

Fig.9

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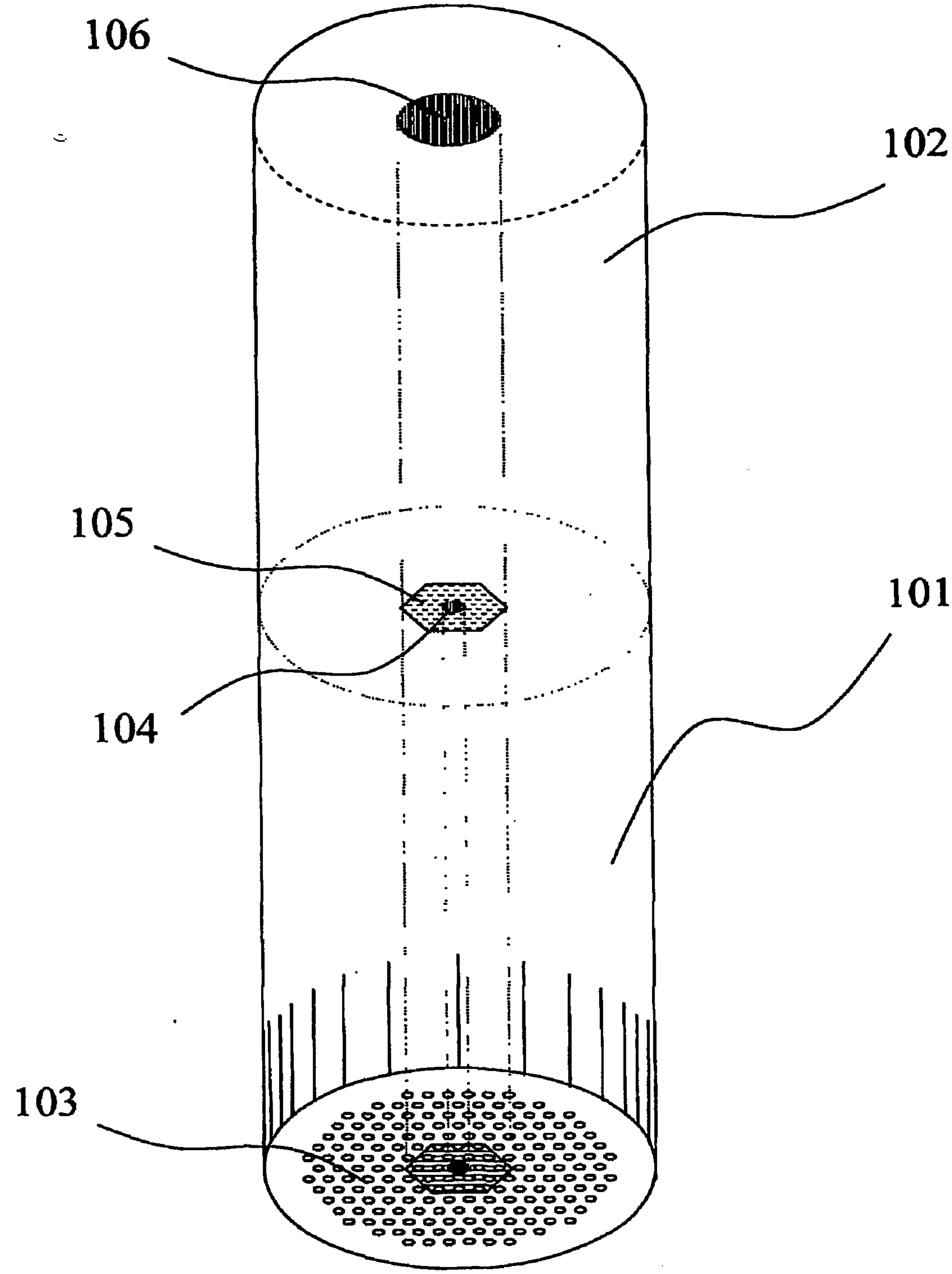

Fig.10

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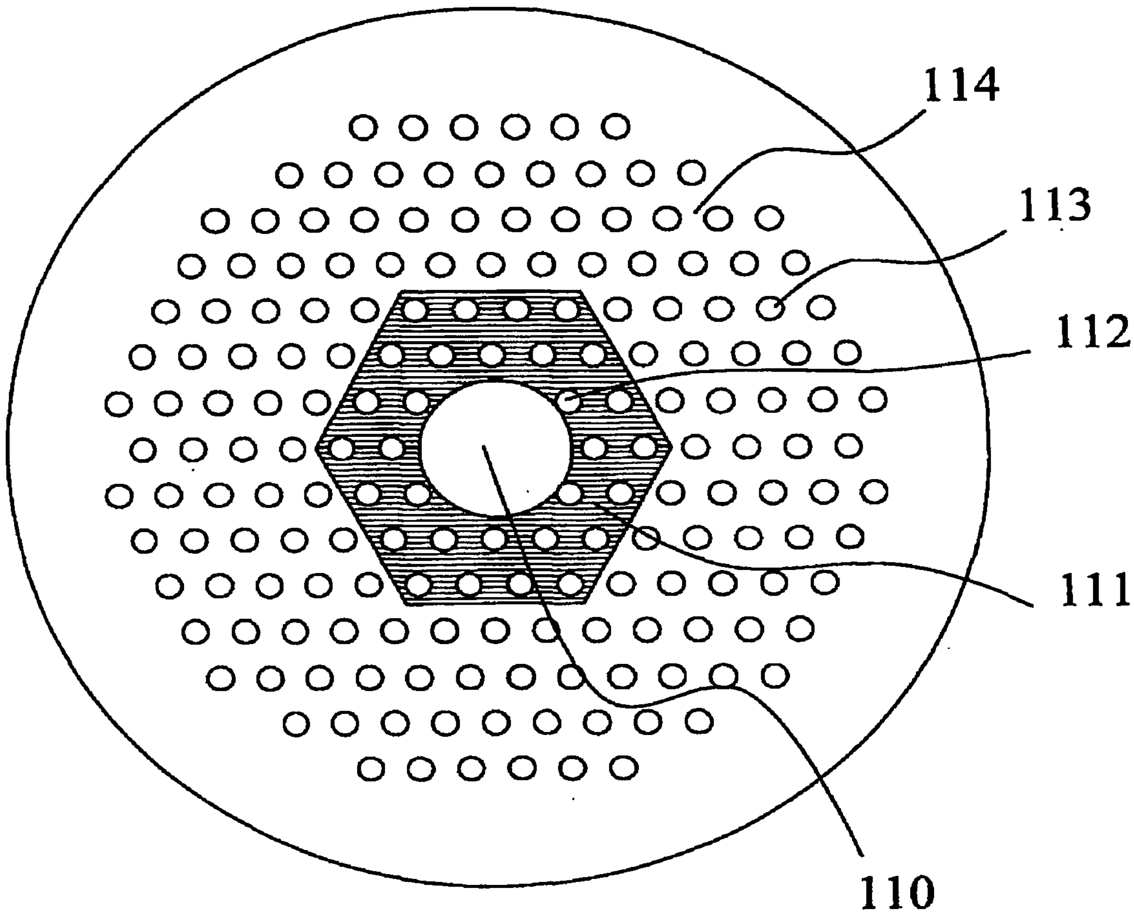

Fig.11

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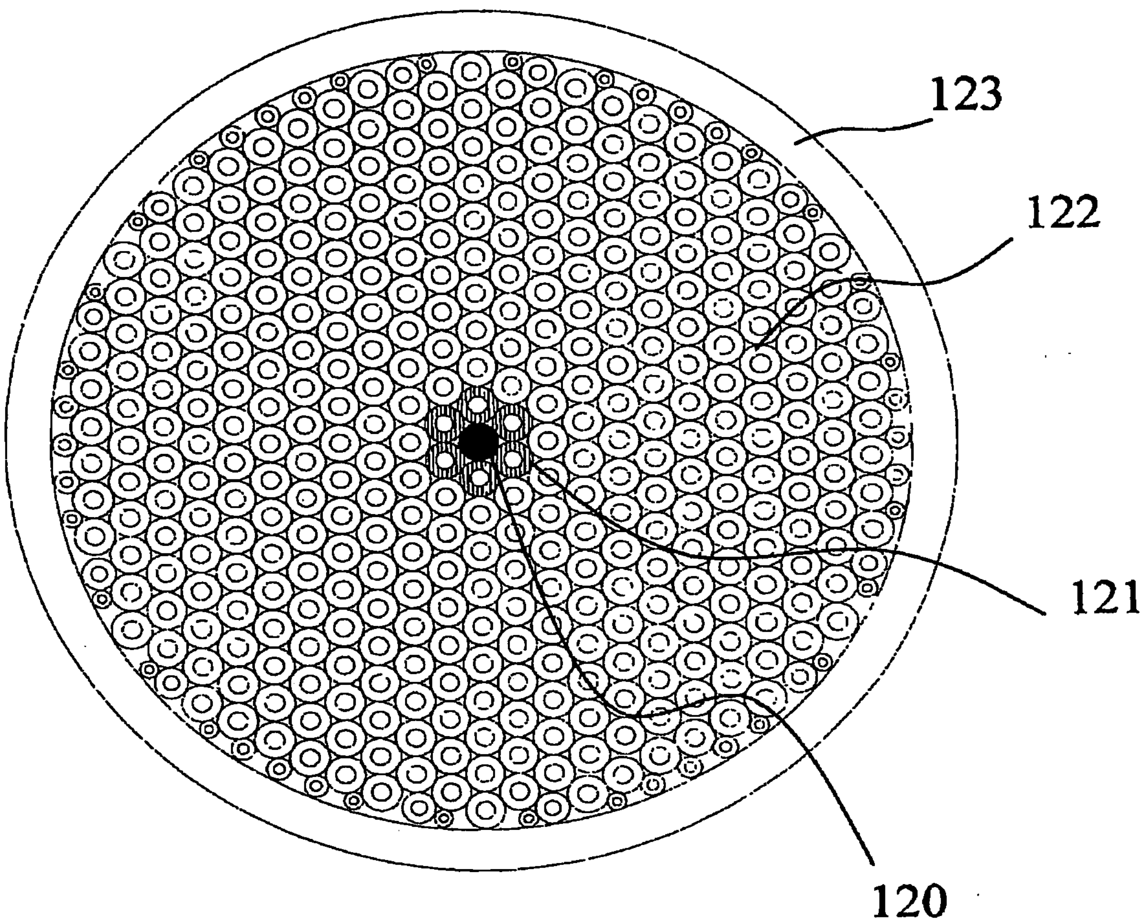

Fig.12